

The magic of magnetic multilayers¹

by S. S. P. Parkin
Guest Editor

In recent years there has been a renaissance in the study of magnetic multilayers—primarily because of the discoveries of enhanced or giant magnetoresistance [1, 2] and oscillatory interlayer exchange coupling [3] in magnetic multilayered structures consisting of alternating thin ferromagnetic and nonferromagnetic metallic layers. These discoveries have led to intense theoretical and experimental studies of an extraordinary range of structures over the past few years.

Giant magnetoresistance (GMR) is displayed by a wide variety of inhomogeneous magnetic nanostructures consisting of magnetic entities, for example, thin layers or particles, separated by thin nonferromagnetic metallic spacer layers. The original observation of GMR was made in single-crystalline (100) Fe/Cr “sandwich” and superlattice structures grown by molecular beam epitaxy (MBE) in ultrahigh-vacuum deposition chambers. It had previously been found that the magnetic moments of the Fe layers in a (100)-oriented Fe/Cr/Fe sandwich are aligned antiparallel to one another in zero field when the Cr layer is about 9 Å thick [4]. When a sufficiently large magnetic field is applied, the moments of the Fe layers become aligned parallel with one another. The resistance of such sandwiches or superlattices comprising many such sandwiches depends upon the magnetic arrangement of the magnetic layers and was observed to be higher when the moments are aligned antiparallel to one another. The magnetoresistance of such structures is much larger than

that of the intrinsic magnetoresistance of the Fe layers themselves and is especially large at low temperatures.

While the observation initially appeared to be somewhat esoteric, it was found soon afterward that similar results could be obtained in polycrystalline Fe/Cr structures grown by the much simpler technique of magnetron sputtering [3]. These experiments also revealed that GMR could be observed in a wide variety of transition-metal magnetic multilayers. In addition, the experiments showed, in contrast to the earlier work on MBE-grown structures, that the magnitude of the GMR effect oscillated as the thickness of the nonferromagnetic spacer layers between the ferromagnetic layers was increased. This oscillation was shown to be caused by an oscillation in the sign of the interlayer exchange coupling between the ferromagnetic layers. The coupling was shown to oscillate between antiferromagnetic and ferromagnetic coupling such that the magnetic moments of successive ferromagnetic layers were either parallel (ferromagnetic) or antiparallel (antiferromagnetic) in small magnetic fields.

Oscillatory coupling was shown to be a very general property of almost all transition-metal magnetic multilayered systems in which the nonferromagnetic layer comprises one of the 3d, 4d, or 5d transition metals or one of the noble metals [5]. The oscillation period was found to be just a few atomic layers, typically about 10 Å, but varying up to ~20 Å. Only those multilayers for which the interlayer coupling is antiferromagnetic display significant giant magnetoresistance effects. It is only in those systems that the relative orientation of the magnetic moments of neighboring layers is significantly altered by applying a magnetic field.

¹Introduction to papers in this issue on giant magnetoresistance (GMR), oscillatory interlayer exchange coupling in magnetic multilayers, and related studies.

Magnetron sputtering allowed the study of many different magnetic multilayered systems. One of these systems, namely ferromagnetic cobalt layers separated by thin copper layers, was found to exhibit very large GMR effects even at room temperature [6, 7]. Values of GMR in Co/Cu multilayers exceed 110% at room temperature² [7]. While the largest GMR values require magnetic fields exceeding ~20 kOe, magnetoresistance values of 50–60% are obtained in fields of several hundred oersteds and values of ~20% or more in fields of a few tens of oersteds. These lower values are obtained by using thicker Cu layers, for which the interlayer exchange coupling is weaker. Such large magnetoresistance values at room temperature make such multilayers attractive candidates for a variety of technological applications. Moreover, the fact that these multilayers are readily formed using deposition techniques compatible with large-scale manufacturing makes them even more alluring.

Magnetoresistive materials are used in a wide variety of applications for detecting magnetic fields. For some applications, such as the detection of the rotation of a spinning object, as for example in anti-lock brake systems in automobiles, relatively large magnetic fields can be used. For other applications, such as the detection of magnetic bits in a hard disk drive, materials whose resistance is sensitive to quite small magnetic fields are needed. Conventional materials such as Ni-Fe alloys exhibit resistance changes at room temperature of just a few percent in magnetic fields of a few oersteds. GMR sandwiches can achieve sensitivities to such fields of perhaps as much as five times greater than conventional materials.

GMR multilayered structures have already found their way into leading-edge hard disk drive products. Early in November 1997, IBM was the first company to announce GMR magnetic recording read heads in a family of disk drive products, designated Deskstar* 16GP. First customer shipment began in January 1998. In these products, the use of GMR read heads allows the reading of extremely small magnetic bits at an areal density of 2.69 gigabits per square inch. The capacity of a hard disk drive is largely determined by the areal density in conjunction with the size and number of disks or platters within the drive. GMR read heads allow more than 3.2 gigabytes of data to be stored on each 95-mm-diameter disk of the Deskstar 16GP disk drives. The resulting data storage capacity of these "3.5-inch form-factor" drives is 16.8 gigabytes. The areal density of hard disk drives, driven by the rapid evolution of the various technologies involved, is increasing at a compound growth rate of about 60% per year, and by the year 2001 is expected to reach 10 gigabits per square inch.

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²S. S. P. Parkin, "110% GMR in (110) Co/Cu Multilayers," unpublished work.

This issue of the *IBM Journal of Research and Development* discusses some of the work carried out over the past few years, largely within IBM, concerning GMR, oscillatory interlayer exchange coupling in magnetic multilayers, and related effects.

The first paper, by Allenspach and Weber, discusses some experiments which probe the origin of the oscillatory interlayer coupling in single-crystal (100)-oriented Co/Cu/Co sandwiches prepared on single-crystal Cu substrates. These experiments have shown that the strength and period of the oscillatory coupling could largely be explained from the well-known electronic properties of Cu. In these experiments, the thickness of the Cu and Co layers could be varied by fractions of an atomic layer, and it was observed that the magnetic properties of this system depend on such minute variations.

The second paper, by Jones, discusses some of the different theoretical approaches used to understand oscillatory interlayer coupling. In particular, Jones discusses the role of quantized electronic states in magnetic multilayers and their dependence on the magnetic structure of the multilayer.

In the following paper, Himpsel et al. discuss the experimental observation of such quantum-well states in (100) Co/Cu using spin-polarized photoemission spectroscopy and the relationship of such states to both interlayer coupling and GMR.

While sputter-deposition techniques account for many of the major developments in the field of magnetic multilayers in recent years, MBE continues to be a valuable technique for the growth of certain single-crystalline systems. Farrow discusses the role MBE has played in developing an understanding of certain aspects of GMR and oscillatory interlayer coupling. Much work was applied to understanding why single-crystalline (111)-oriented Co/Cu multilayers grown by MBE show no GMR, whereas polycrystalline (111)-textured Co/Cu multilayers grown by sputter deposition show very large GMR values. For many years this was a puzzle which was addressed by many groups. It is now generally believed that imperfections in the MBE-prepared multilayers account for this behavior. The use of advanced materials growth techniques, such as the use of surfactants to promote smoother films, has finally led to the observation of oscillatory interlayer coupling in MBE-grown (111) Co/Cu. These studies emphasize that subtle structural modifications of magnetic multilayers can lead to dramatically altered properties.

Nesbet reviews theories of GMR and, in particular, discusses models of GMR based on realistic band structures of the metals involved. These models demonstrate the importance of the scattering at the interfaces between the ferromagnetic and

nonferromagnetic layers in GMR. The importance of interface scattering to GMR, originally demonstrated in experiments which modified the interfaces [8], is now widely accepted and is of particular technological significance.

In recent years there have been many advances in experimental techniques for probing aspects of the structure and magnetism of magnetic layers and multilayers. Stöhr and Nakajima discuss the use of advanced synchrotron-based techniques to probe, with elemental specificity, not only the magnetic moments of the ferromagnetic layers in magnetic multilayers but also the magnetism of the nonferromagnetic layers. Copper layers in Co/Cu multilayers become magnetically active by virtue of their proximity to the ferromagnetic Co layers. By contrast, in Fe/Cu structures, the ferromagnetic Fe layers can become magnetically inactive because of the structural influence of the Cu layers.

In the paper which follows, Sun et al. discuss recent developments in an entirely different class of materials: the manganite perovskites. These materials show extremely large changes in resistance in magnetic fields, but typically at temperatures well below room temperature and in extremely large magnetic fields. The origin of their magnetoresistance, commonly referred to as colossal magnetoresistance, is quite different from the GMR of magnetic multilayers. In my opinion, it is unlikely that such materials will be useful technologically because of their great complexity as well as the strong temperature dependence of their properties. In contrast to these materials, GMR multilayered structures have already found important technological applications.

In the final paper of the group, Tsang et al. discuss the use of specially engineered GMR structures for hard disk drive read-head applications. As mentioned above, GMR multilayered structures can display very large magnetoresistance values, but at relatively large magnetic fields. In a magnetic recording disk drive, information is stored as magnetized regions within thin magnetic layers (which themselves can be rather complicated multilayered thin-film structures) deposited onto aluminum or glass platters. The regions are magnetized longitudinally within the plane of the platter either parallel or antiparallel to the circumference of the platter. It is the transitions between these magnetized regions which are detected by a magnetic recording read head via the magnetic flux emanating from the transition regions. The strength of the magnetic field at the read head is only a few tens of oersteds. Thus, a field-sensing device capable of detecting such small magnetic fields is required.

GMR magnetic multilayered structures can be engineered to be sensitive to such small fields with greater sensitivity than conventional ferromagnetic metals. For example, this can be achieved by forming simple

sandwiches of two ferromagnetic metals separated by a thin layer of Cu perhaps 20 Å thick. One of the ferromagnetic layers is magnetically hardened so that for the range of magnetic fields to which it is subjected, the magnetic moment of that layer is fixed. This can be achieved by coupling that ferromagnetic layer to a thin antiferromagnetic layer using the phenomenon of exchange biasing. In addition, one takes advantage of the fact that whereas the GMR effect falls off very slowly with increasing separation of the ferromagnetic layers for Cu spacer layers, the magnitude of the interlayer exchange coupling decreases much more rapidly with increasing Cu thickness. Thus, the intrinsic magnetic coupling through Cu layers 20 Å thick is weak. The moment of the second ferromagnetic layer in the GMR sandwich rotates in the presence of the magnetic field from the transition region and thus causes a change in the resistance of the sandwich. The variation in the resistance of the sandwich is used to detect the transition region between the magnetic bits, and thus the stored data can be recovered. This type of GMR sandwich has been termed a spin-valve GMR sandwich [9]. Tsang et al. discuss the optimization of GMR multilayered structures for high-density magnetic recording read-head applications. For such applications, very thin ferromagnetic sense layers are needed. One of the main reasons why GMR structures provide a greater signal for these applications than conventional ferromagnetic alloys is the predominant interfacial origin of GMR, which typically results in a larger GMR signal for thinner ferromagnetic layers.

The papers included in the GMR-related portion of this issue cover just a small subset of the work carried out within IBM over the past few years on magnetic multilayers and related structures. This work is itself just a small subset of that carried out within the scientific community. It is perhaps remarkable that within less than a decade, magnetic multilayers have evolved from a scientific curiosity to become materials of significant technological importance.

This class of magnetic multilayers has revealed a considerable number of scientific insights. In addition, the study of its properties has led to significant developments in the preparation of magnetic multilayered structures with layers just two or three atomic layers thick. Such structures can now be prepared routinely and with sufficient reproducibility for commercial applications. Advances in structural, magnetic, and electronic characterization have helped to motivate continuing interest in such structures. In the future, studies seem likely to evolve to the study of lower-dimensional magnetic nanostructured materials patterned or structured into lines or dots.

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